RADIOMETRIC CALIBRATION

VISIBLE/INFRARED IMAGER/RADIOMETER SUITE ALGORITHM THEORETICAL BASIS DOCUMENT

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GLOSSARY OF ACRONYMS

A-D	Analog to Digital
ADC	Analog to Digital Conversion
ATBD	Algorithm Theoretical Basis Document
AVHRR	Advanced Very High Resolution Radiometer
BB	Blackbody
BRDF	Bi-directional Reflectance Distribution Function
CCA	Circuit Card Assembly
CDR	Critical Design Review
CCD	Charge Coupled Device
DN	Digital Number
DNB	Day/Night Band
DoD	Department of Defense
DPA	Data Processing Architecture
EDR	Environmental Data Record
EOS	Earth Observing System
FPA	Focal Plane Assembly
GIFOV	Ground Instantaneous Field of View
HAM	Half Angle Mirror
HSI	Horizontal Sampling Interval
HSR	Horizontal Spatial Resolution
IP	Intermediate Product
IPO	Integrated Program Office
LLLS	Low Level Light Sensor
LUT	Lookup Table
MCST	MODIS Characterization Support Team
MODIS	Moderate Resolution Imaging Spectroradiometer
NASA	National Aeronautics and Space Administration
NOAA	National Oceanic and Atmospheric Administration
NPOESS	National Polar-orbiting Operational Environmental Satellite System
NPP	NPOESS Preparatory Project
OLS	Operational Linescan System
PDR	Preliminary Design Review
PS	Performance Specification
RDR	Raw Data Record
RVS	Response Versus Scan
SBRS	Santa Barbara Remote Sensing
SDR	Sensor Data Record
SDSM	Solar Diffuser Stability Monitor
SIS	Spherical Integrating Source

SNR	Signal-to-Noise Ratio
SRD	Sensor Requirements Document
TIROS	Television Infrared Observation Satellite
TOA	Top of Atmosphere
TP	Technical Publication
TV	Thermal Vacuum
VIIRS	Visible/Infrared Imager/Radiometer Suite
VIS/NIR	Visible/Near Infrared

ABSTRACT

The Visible/Infrared Imager/Radiometer Suite (VIIRS) is scheduled to fly onboard multiple satellites in the National Polar-orbiting Operational Environmental Satellite System (NPOESS). It will produce many science data products, each of which is referred to as an Environmental Data Record (EDR). The VIIRS EDR requirements are described in detail in the VIIRS Sensor Requirements Document (SRD). These requirements form the foundation from which both the algorithms and the sensor are designed and built. A revised version of the SRD was released in November 1999. It included a set of new requirements targeted toward the NPOESS Preparatory Project (NPP); a National Aeronautics and Space Administration (NASA) endeavor to build upon the heritage of the Moderate Resolution Imaging Spectroradiometer (MODIS) beginning in 2005. Incremental updates to the SRD have followed with minor changes. At the time of this writing Version 3, dated June 2000, is the latest issue.

Most of the VIIRS EDR algorithms require radiometric data input from one or more VIIRS spectral bands. These data are generally ingested in one of three forms:

- Calibrated Top of Atmosphere (TOA) Radiances
- Calibrated TOA Reflectances
- Calibrated TOA Brightness Temperatures

Each of these forms is included in resolution specific Sensor Data Record (SDR) files. The SDR structures are very basic and draw heavily upon heritage for similar Level 1 products.

This document describes the algorithms for converting geolocated digital numbers (i.e. instrument counts) from each verified VIIRS Raw Data Record (RDR) into these SDR products. MODIS emissive band and reflective band Level 1B algorithms provided the baseline for VIIRS. Enhancements to these heritage algorithms were made to accommodate features that are unique to VIIRS, including dual gain bands, the Day/Night Band (DNB), and the along-scan aggregation of sub-pixel detectors. These algorithms apply calibration coefficients determined during pre-launch testing and updated as needed to transfer the ground calibration to on-orbit data. Provisions are included to incorporate adjustments into the radiometric calibration to account for instrument temperature, changes in incoming solar flux, and to correct for instrument degradation.

1.0 INTRODUCTION

This Algorithm Theoretical Basis Document (ATBD) describes the algorithm used to produce calibrated top of atmosphere (TOA) radiances, calibrated TOA reflectances, and calibrated TOA brightness temperatures for National Polar-orbiting Operational Environmental Satellite System (NPOESS) Visible/Infrared Imager/Radiometer Suite (VIIRS) sensor data. These are the primary Sensor Data Record (SDR) products of the VIIRS. The main purpose of this ATBD is to establish guidelines for the production of these SDR products. This document describes the required inputs, the theoretical and mathematical description of the retrieval algorithm, practical considerations for implementation, and the assumptions and limitations associated with the products.

Throughout this document are references to other Raytheon Santa Barbara Remote Sensing (SBRS) documents. These references use the SBRS document number set in italic font and enclosed in brackets (e.g. *[Y12345]*). When a document is first referenced its complete title is given along with the document number.

1.1 PURPOSE AND SCOPE OF DOCUMENT

This ATBD is part of the VIIRS Algorithm Subsystem's documentation hierarchy as called for in the VIIRS Software Development Plan *[Y2388]*. As shown in Figure 1 the Algorithm Subsystem Specification *[PS154640-102]* is the controlling document for this ATBD. The software architecture for implementing the radiometric calibration algorithms is documented separately.

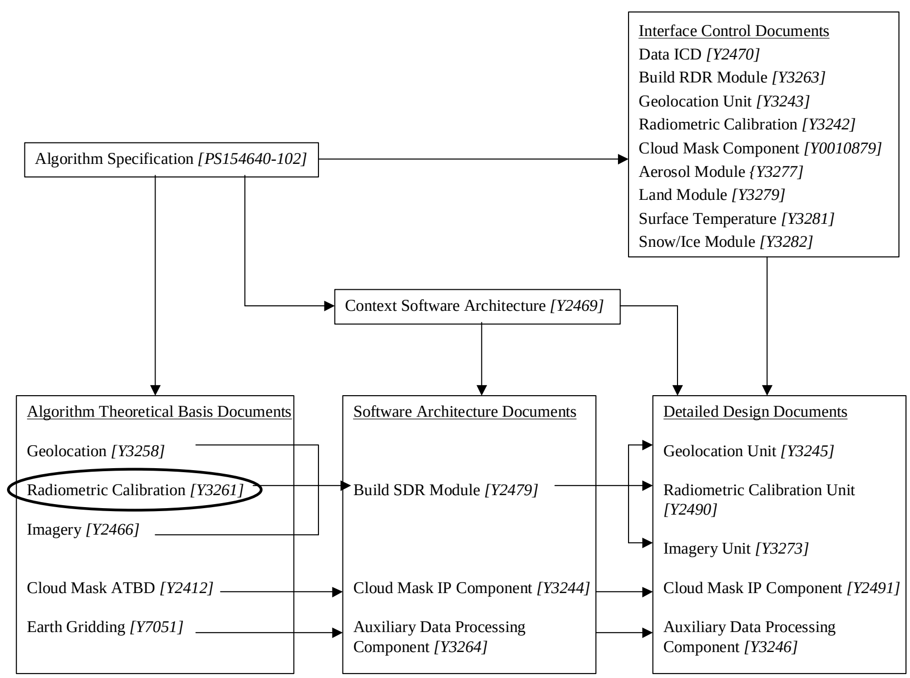

Figure 1. Hierarchy of VIIRS documents that relate to the design of the RDR to SDR s/w. (this ATBD is circled)

This document covers the algorithm theoretical basis for the operational retrieval of calibrated TOA radiances, calibrated TOA reflectances, and calibrated TOA brightness temperatures. Any derived products beyond these three SDR products are not discussed beyond brief mention. The geolocation part of the Raw Data Record (RDR) to SDR conversion process is discussed in the VIIRS Geolocation ATBD *[Y3258]*. Information concerning the pre-flight calibration of VIIRS and the transfer of this calibration to on-orbit data is in the VIIRS Characterization and Calibration Plan (TP 154640-118).

This version of the Radiometric Calibration ATBD is focused on that part of the radiometric calibration that is needed for the near real-time operational conversion of raw instrument counts to radiances, reflectances, and brightness temperatures. The term digital number (DN) is used throughout this document to refer to raw instrument counts. The processing required to derive and update calibration coefficients and correction factors based on the results obtained during the offline analysis of on-orbit calibration mode data is outside the present scope of this document.

1.2 DOCUMENT CONTEXT, CONVENTIONS, AND ORGANIZATION

The organization of this ATBD is to provide introductory information in Section 1. Section 2 provides a brief overview of radiometric calibration including VIIRS instrument characteristics and the radiometric calibration timeline. Section 3 contains the essence of this document—a complete description of the operational radiometric calibration algorithm. Consideration is given to the overall structure, the required inputs, a theoretical description of the products, and practical implementation issues. Section 4 identifies the assumptions and limitations of the radiometric calibration algorithm and Section 5 contains a listing of document references that are cited throughout this document.

Version 5 is the third working version of this document and is a VIIRS Critical Design Review (CDR) deliverable. It is dated March 2002. At the time of writing some of the fine details of the VIIRS sensor design were not finalized. Constants related to the VIIRS design and operation are included in this document as representative of the VIIRS flight models. The actual values for each sensor may vary from those that are presented in this document version.

The previous version number (version 4) was issued in May 2001 to address comments received from the VIIRS Preliminary Design Review (PDR). Version 3 was the first version of this ATBD. Its version number was chosen to match the delivery of the previously existing VIIRS EDR ATBDs, which had undergone two previous version releases. Shawn W. Miller and Douglas V. Hoyt authored the Version 3 ATBD (then called “RDR to SDR Conversion ATBD”).

2.0 OVERVIEW

2.1 OBJECTIVES OF RADIOMETRIC CALIBRATION

One or more of the SDR products described in this document are necessary inputs to most of the VIIRS Environmental Data Record (EDR) algorithms. All VIIRS EDR algorithms use these data either directly or indirectly. These SDR products form the link between sensor measurements and algorithm inputs, relating collected photons at the sensor aperture to radiance fields at the top of the atmosphere, which in turn are related via the EDR algorithms to surface and/or atmospheric properties.

2.1.1 Requirements Summary

The requirements for the radiometric calibration part of the VIIRS Data Processing Architecture (DPA) are in the Performance Specification Algorithm Specification for the VIIRS *[PS154640-102]*. The DPA is presented in the VIIRS Context Software Architecture *[Y2469]*.

2.1.2 Data Products

The radiometric calibration part of the VIIRS DPA will produce the following during operational near real-time processing:

- Sensor Data Record (SDR) files
- On-board Calibrator Intermediate Product (IP) files
- Calibrated Dual Gain IP files

The SDR files will contain the calibrated TOA radiances, reflectances, and brightness temperatures as well as geolocation and related information including geodetic latitude and longitude, terrain height, and satellite, solar, and lunar geometry at each VIIRS pixel. Details concerning the SDR files can be found in the VIIRS Radiometric Calibration Unit Level Detailed Design *[Y2490]*.

The On-board Calibrator IP files contain subsets of each RDR and will be the primary input to offline VIIRS performance analysis. Included in these subsets are all raw calibrator view DNs as well as engineering and housekeeping data. Details concerning this IP can also be found in the VIIRS Radiometric Calibration Unit Level Detailed Design *[Y2490]*.

The Calibrated Dual Gain IP files contain unaggregated, calibrated TOA radiances, reflectances, and brightness temperatures for those VIIRS observations that are aggregated along-scan during ground processing into VIIRS pixels prior to storage in the SDR files; i.e. the calibrated dual gain band data from the nadir and near-nadir aggregation zones before aggregation. Details concerning this IP can also be found in the VIIRS Radiometric Calibration Unit Level Detailed Design *[Y2490]*.

2.2 SENSOR OVERVIEW

The VIIRS can be considered as a convergence of three existing sensors; the Operrational Linescan System (OLS), the Advanced Very High Resolution Radiometer (AVHRR), and the Moderate Resolution Imaging Spectroradiometer (MODIS). The OLS and AVHRR have seen extensive operational use. At the time of this writing the MODIS has been operational for approximately two years.

The OLS is the operational visible/infrared scanner for the Department of Defense (DoD). Its unique strengths are controlled growth in spatial resolution through rotation of the ground instantaneous field of view (GIFOV) and the existence of a low-level light sensor (LLLS) capable of detecting visible radiation at night. OLS has primarily served as a data source for manual analysis of imagery. The AVHRR is the operational visible/infrared sensor flown on the National Oceanic and Atmospheric Administration (NOAA) Television Infrared Observation Satellite (TIROS-N) series of satellites (Planet, 1988). Its unique strengths are low operational and production cost and the presence of five spectral channels that can be used in a wide number of combinations to produce operational and research products. In December 1999, the National Aeronautics and Space Administration (NASA) launched the Earth Observing System (EOS) morning satellite, *Terra*, which includes the MODIS. This sensor possesses an unprecedented array of thirty-two spectral bands at resolutions ranging from 250 m to 1 km at nadir, allowing for unparalleled accuracy in a wide range of satellite-based environmental measurements.

A VIIRS will be carried aboard each platform of the National Polar-orbiting Operational Environmental Satellite System (NPOESS). NPOESS is a joint mission between DoD, NOAA and NASA. The VIIRS is a single visible/infrared sensor capable of satisfying the needs of all three communities, as well as the general research community. As such, the VIIRS will have three key attributes: high spatial resolution with controlled growth off nadir, low production and operational cost, and a large number of spectral bands to satisfy the requirements for generating accurate operational and scientific products.

The VIIRS spectral bands as compared to MODIS, OLS, and AVHRR are shown in Table 1. The spectral position of the VIIRS bands is summarized in Figure 2 through Figure 5. The VIIRS moderate and imagery resolution bands are distributed among three focal plane assemblies (FPA). As shown in Figure 6 each moderate resolution band consists of sixteen along-track detectors and each imagery resolution band consists of thirty-two along-track detectors with odd numbered detectors staggered relative to even numbered detectors. The VIIRS Day/Night Band (DNB) is a temperature controlled Charge Coupled Device (CCD) that is mounted to the visible/near-infrared (VIS/NIR) FPA. The DNB has 672 sub-pixel detectors along-track that are aggregated on-board to create sixteen constant 740 m pixels across the scan.

Figure 7 illustrates the design concept for the VIIRS, which is being designed and built by Raytheon Santa Barbara Remote Sensing (SBRS). At its heart is a rotating telescope scanning mechanism that minimizes the effects of solar impingement and scattered light. Calibration will be performed onboard using a solar diffuser for short wavelengths and a V-groove blackbody and deep space view for thermal wavelengths. A solar diffuser stability monitor (SDSM) is also included to track the performance of the solar diffuser. The nominal altitude for an NPOESS satellite will be 833 km. The VIIRS scan will extend to 56 degrees on each side of nadir.

Table 1. VIIRS spectral bands as compared to other Vis/IR instruments.

VIIRS			MODIS Equivalent			AVHRR-3 Equivalent			OLS Equivalent		
VIIRS Band	Spectral Range (um)	Nadir HSR (m)	Band(s)	Range	HSR	Band	Range	HSR	Band	Range	HSR
DNB	0.500 - 0.900								HRD PMT	0.580 - 0.910 0.510 - 0.860	550 2700
M1	0.402 - 0.422	750	8	0.405 - 0.420	1000						
M2	0.436 - 0.454	750	9	0.438 - 0.448	1000						
M3	0.478 - 0.498	750	3 10	0.459 - 0.479 0.483 - 0.493	500 1000						
M4	0.545 - 0.565	750	4 12	0.545 - 0.565 0.546 - 0.556	500 1000						
I1	0.600 - 0.680	375	1	0.620 - 0.670	250	1	0.572 - 0.703	1100			
M5	0.662 - 0.682	750	13 14	0.662 - 0.672 0.673 - 0.683	1000 1000	1	0.572 - 0.703	1100			
M6	0.739 - 0.754	750	15	0.743 - 0.753	1000						
I2	0.846 - 0.885	375	2	0.841 - 0.876	250	2	0.720 - 1.000	1100			
M7	0.846 - 0.885	750	16	0.862 - 0.877	1000	2	0.720 - 1.000	1100			
M8	1.230 - 1.250	750	5	SAME	500						
M9	1.371 - 1.386	750	26	1.360 - 1.390	1000						
I3	1.580 - 1.640	375	6	1.628 - 1.652	500						
M10	1.580 - 1.640	750	6	1.628 - 1.652	500	3a	SAME	1100			
M11	2.225 - 2.275	750	7	2.105 - 2.155	500						
I4	3.550 - 3.930	375	20	3.660 - 3.840	1000	3b	SAME	1100			
M12	3.660 - 3.840	750	20	SAME	1000	3b	3.550 - 3.930	1100			
M13	3.973 - 4.128	750	21 22 23	3.929 - 3.989 3.929 - 3.989 4.020 - 4.080	1000 1000 1000						
M14	8.400 - 8.700	750	29	SAME	1000						
M15	10.263 - 11.263	750	31	10.780 - 11.280	1000	4	10.300 - 11.300	1100			
I5	10.500 - 12.400	375	31 32	10.780 - 11.280 11.770 - 12.270	1000 1000	4 5	10.300 - 11.300 11.500 - 12.500	1100 1100	HRD	10.300 - 12.900	550
M16	11.538 - 12.488	750	32	11.770 - 12.270	1000	5	11.500 - 12.500	1100			

The VIIRS Sensor Requirements Document (SRD) places explicit requirements on spatial resolution for the Imagery EDR. Specifically, the horizontal spatial resolution (HSR) of bands used to meet threshold Imagery EDR requirements must be no greater than 400 m at nadir and 800 m at the edge of the scan. This led to the development of a unique scanning approach which optimizes both spatial resolution and signal to noise ratio (SNR) across the scan. The concept is summarized in Figure 8 for the imagery resolution bands; the nested moderate resolution bands follow the same approach at exactly twice the size. The VIIRS moderate and imagery resolution detectors are rectangular, with the smaller dimension projecting along the scan. At nadir, three detector footprints are aggregated to form a single VIIRS "pixel." Moving along the scan away from nadir, the detector footprints become larger both along track and along scan, due to geometric effects and the curvature of the Earth. The effects are much larger along scan. At around 32 degrees in scan angle, the aggregation scheme is changed from 3x1 to 2x1. A similar switch from 2x1 to 1x1 aggregation occurs at 48 degrees. The VIIRS scan consequently exhibits a pixel growth factor of only 2 both along track and along scan, compared with a growth factor of 6 along scan which would be realized without the use of the aggregation scheme. Figure 9 illustrates the benefits of the aggregation scheme for spatial resolution. The VIIRS Day/Night Band (DNB) will not show this pixel growth as elements of the DNB CCD array will be selected to maintain a constant moderate resolution pixel size across scan.

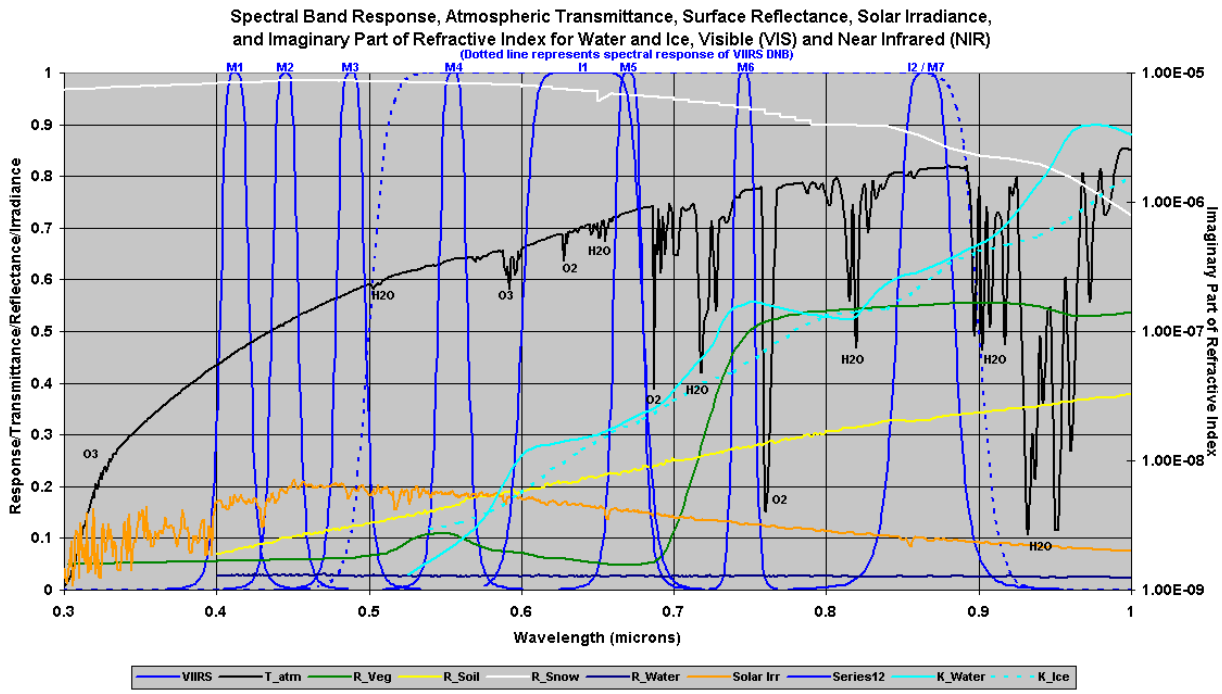

Figure 2. VIIRS spectral bands, visible and near infrared.

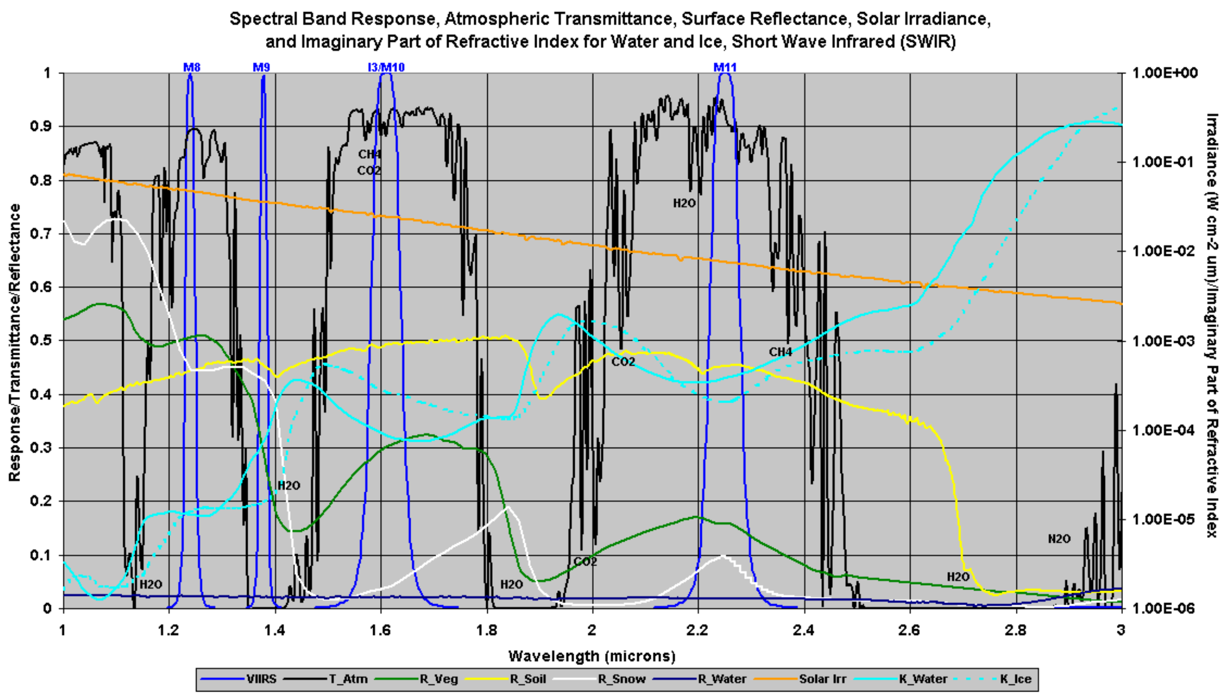

Figure 3. VIIRS spectral bands, shortwave infrared.

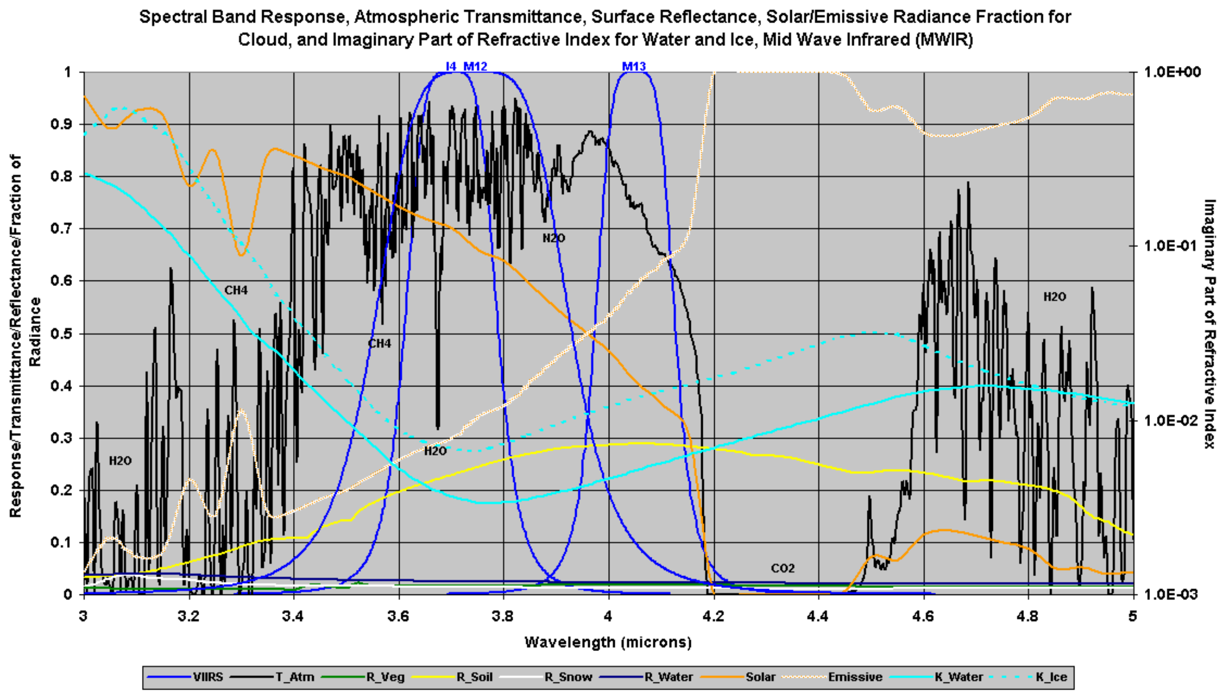

Figure 4. VIIRS spectral bands, midwave infrared.

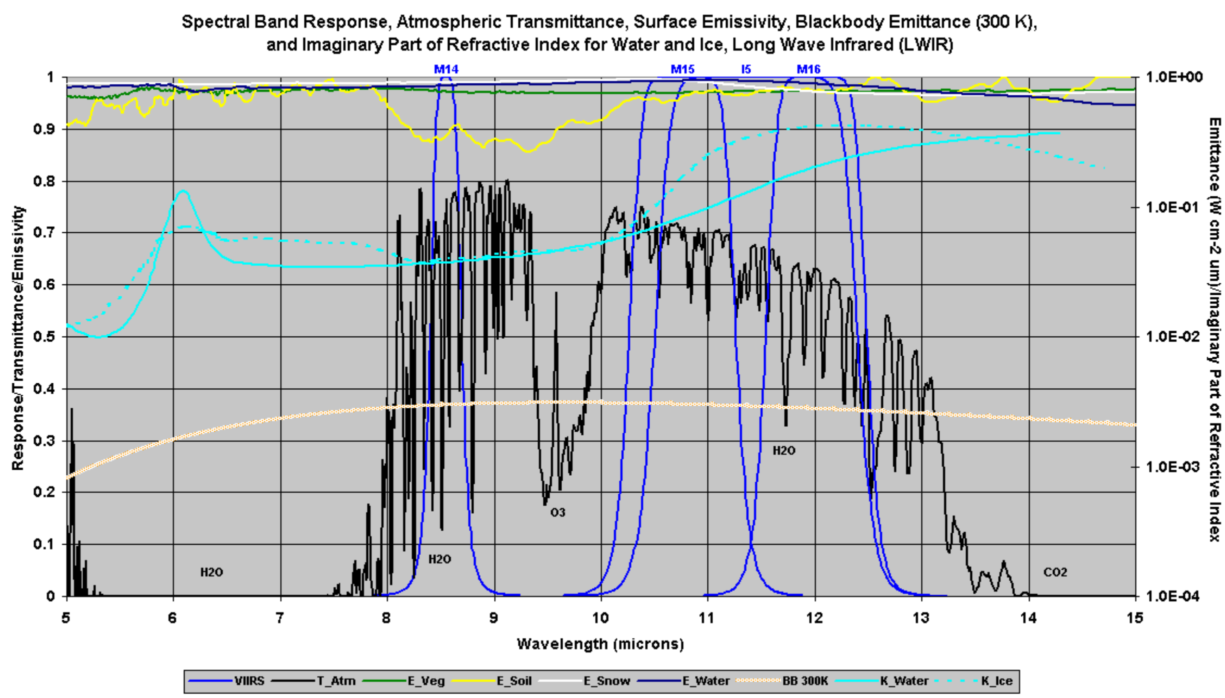

Figure 5. VIIRS spectral bands, longwave infrared.

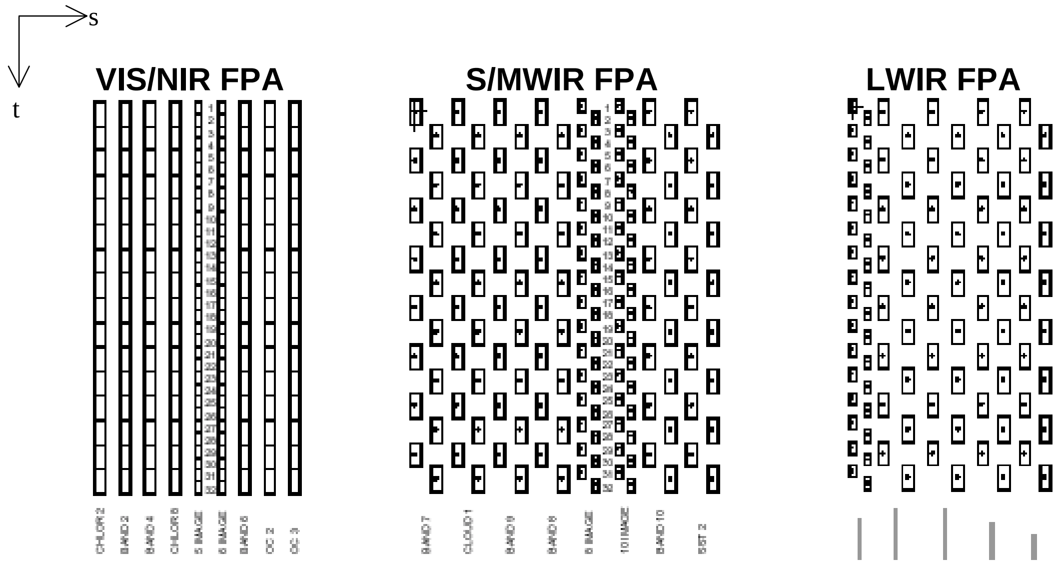

Figure 6. Physical Layout of the Focal Planes.

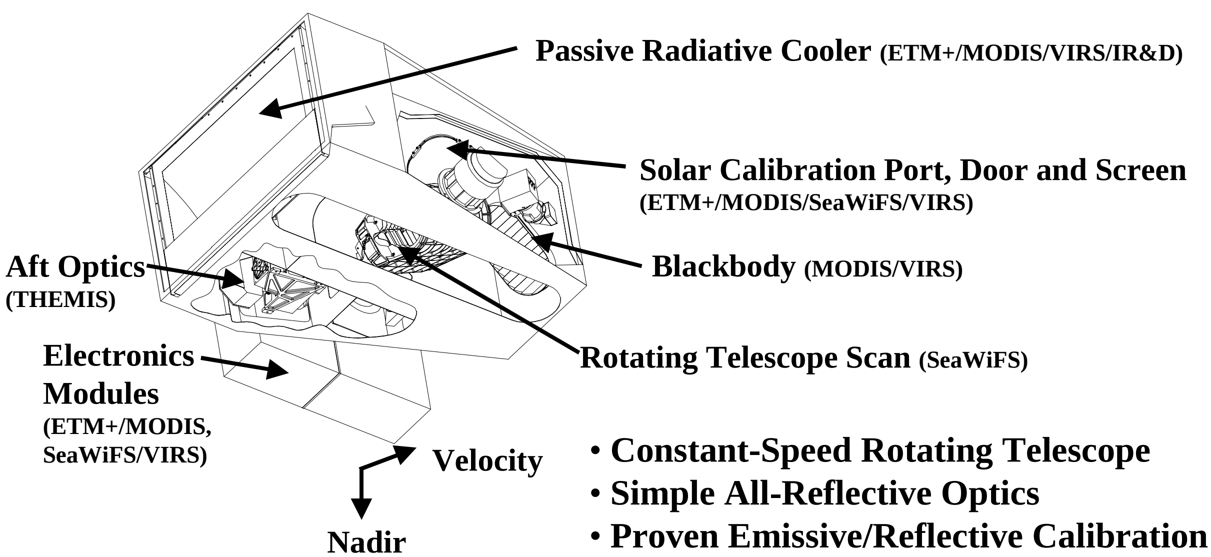

Figure 7. Summary of VIIRS design concepts and heritage.

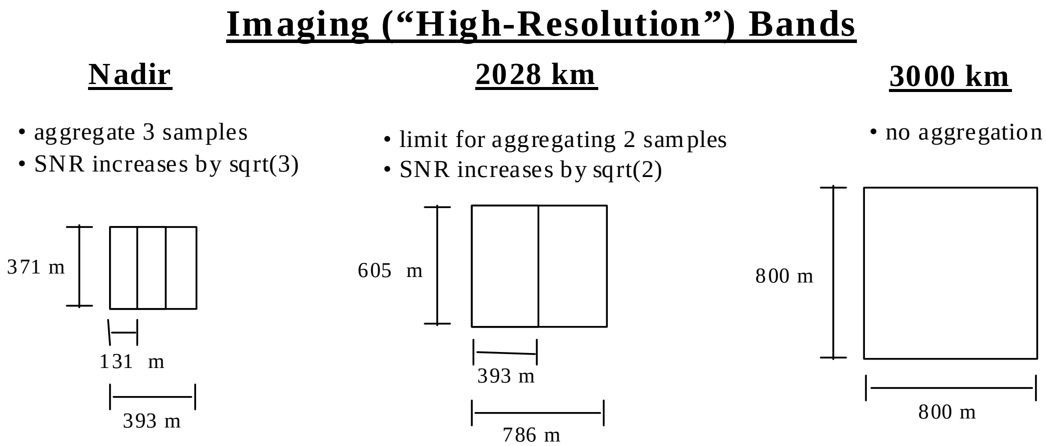

Figure 8. VIIRS detector footprint aggregation scheme for building "pixels." (NOTE: dimensions are approximate)

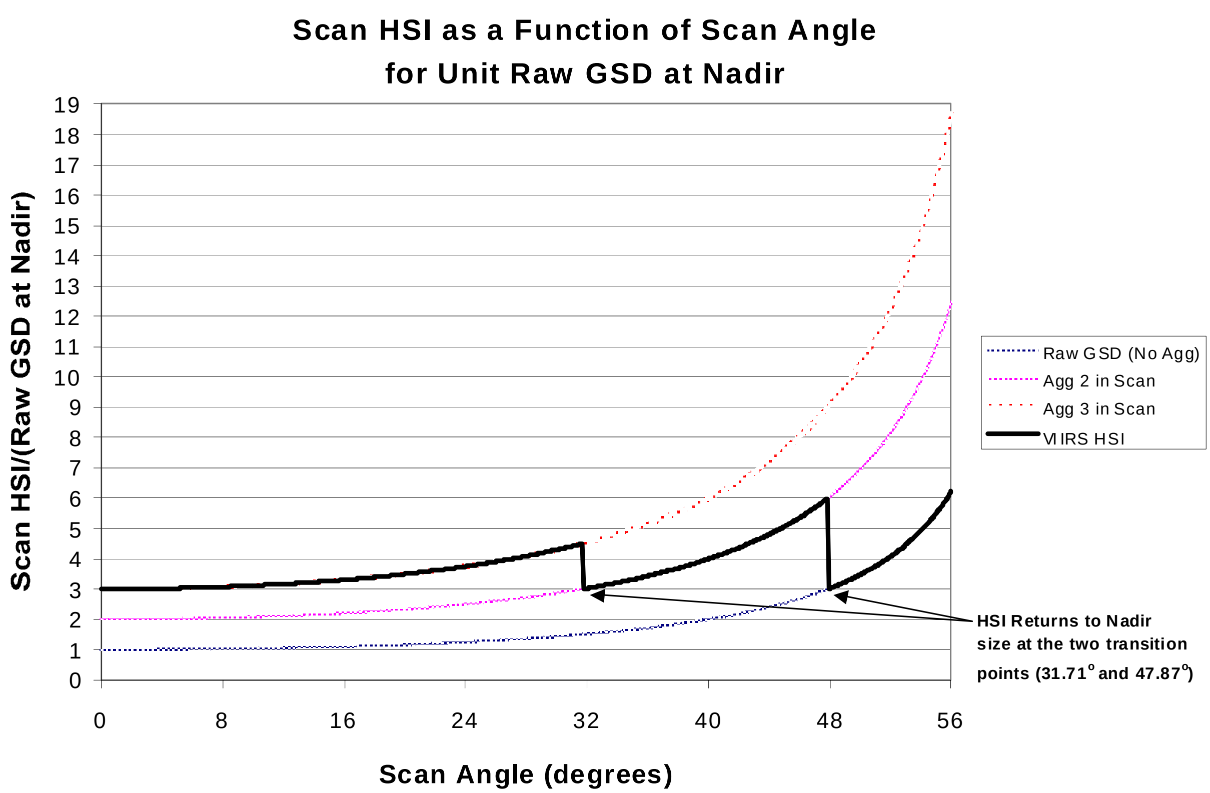

Figure 9. Benefits of VIIRS aggregation scheme in reducing pixel growth at edge of scan.

Some of the VIIRS moderate resolution bands are designed with dual gain in order to cover the required dynamic range within the SNR requirements. The effects of gain switching on radiometric calibration are discussed in the Closure Memo for PDR Action Items 29, 43, 47, and 78 *[Y5563]*.

2.3 RADIOMETRIC CALIBRATION TIMELINE

Radiometric calibration starts early in the VIIRS development and continues through the each sensor's pre-launch testing and mission operations phase.

2.3.1 Pre-Launch

Prior to launch exhaustive tests are performed under ambient and thermal vacuum (TV) conditions to characterize each VIIRS' sensor performance and determine its calibration coefficients. Results from these tests provide the initial data that are stored in reflective, emissive, and DNB radiometric calibration lookup tables (LUTs), which are primary inputs to the operational VIIRS radiometric calibration algorithm.

Calibration for the reflective bands is based on TV measurements of spherical integrating sphere (SIS) radiance and measurements of the Bi-directional Reflectance Distribution Function (BRDF) of the solar diffuser. Calibration of the emissive bands is based on TV measurements of a blackbody (BB) calibration source. Details concerning these pre-launch tests are in the VIIRS Characterization and Calibration Plan *[TP 154640-118]*.

2.3.2 Early Orbit Activation and Evaluation

During early orbit operations sensor performance analysis will occur to test the validity of the pre-launch test results to the processing of on-orbit data (see the VIIRS System Verification and Validation Plan *[TP154640-001]*). Adjustments to the reflective, emissive, and DNB radiometric calibration LUTs will be made as necessary prior to entering the operational phase.

2.3.3 Operations Phase

During operational VIIRS ground processing radiometric calibration will occur early in the VIIRS data retrieval process; immediately following geolocation of the raw pixel data. The calibrated TOA radiances SDR product will be generated for all active bands. The calibrated TOA reflectances SDR product will be generated for all active reflective bands during day and terminator operations. The calibrated TOA brightness temperatures SDR product will be generated for all active emissive bands, including three normally reflective bands, at all times. Table 2 summarizes the bands for which each product will be retrieved.

SDRs will include quality flags to indicate pixels for which radiometric calibration could not be performed.

Table 2. Bands included in the three primary VIIRS SDRs.

Band New (Old)	Center (μm)	SDR_RAD	SDR_REF	SDR_BT	Notes
M1 (Chlor2)	0.412	X	X		Dual Gain
M2 (2)	0.445	X	X		Dual Gain
M3 (Chlor8)	0.488	X	X		Dual Gain
M4 (4)	0.555	X	X		Dual Gain
I1 (5i)	0.645	X	X		Imagery Resolution
M5 (Oc2)	0.672	X	X		Dual Gain
M6 (Oc3)	0.751	X	X		
I2 (6i)	0.865	X	X		Imagery Resolution
M7 (6r)	0.865	X	X	X	Emissive for Fires
M8 (Cloud1)	1.240	X	X	X	Emissive for Fires
M9 (7)	1.378	X	X		
I3 (8i)	1.610	X	X		Imagery Resolution
M10 (8r)	1.610	X	X	X	Emissive for Fires
M11 (9)	2.250	X	X		
M12 (10r)	3.700	X		X	
I4 (10i)	3.740	X		X	Imagery Resolution
M13 (Sst2)	4.050	X		X	Dual Gain
M14 (Sst4)	8.550	X		X	
M15 (11)	10.783	X		X	
I5 (12i)	11.450	X		X	Imagery Resolution
M16 (12r)	12.013	X		X	Dual Output
DNB	0.700	X	X		Day/Night Band

3.0 ALGORITHM DESCRIPTION

3.1 PROCESSING OUTLINE

Radiometric calibration will proceed following the geolocation of VIIRS pixels (see the VIIRS Geolocation ATBD *[Y3258]*). Raw instrument counts (i.e. DN) will be scaled and then calibration coefficients will be applied in accordance with the algorithms presented in Section 3.3.

3.1.1 Near Real-time Processing

In the context of this ATBD near real-time processing refers to the radiometric calibration that will be performed as part of the operational timeline from receipt of downlinked VIIRS RDRs to completion of the corresponding VIIRS EDRs. In general this includes the processing necessary to determine the appropriate zero offsets and correction factor updates to apply to the current Earth view DNs.

3.1.2 Offline Processing

Offline processing includes the processing required to analyze instrument performance, assess sensor degradation, and adjust the slowly varying calibration coefficients that are read into the radiometric calibration unit during near real-time SDR production.

3.2 ALGORITHM INPUTS

3.2.1 VIIRS Data

The required inputs for the generation of SDR products are geolocated RDRs, which contain the basic DNs to be converted into TOA radiance, reflectance, and brightness temperature as well as engineering data and on-board calibrator view data that are required by the radiometric calibration algorithm. Predetermined calibration coefficients and correction factors are read as lookup tables (LUTs) from input parameter files.

3.2.2 Non-VIIRS Data

No non-VIIRS data are required for radiometric calibration except for extraterrestrial solar irradiances, which are needed for offline processing of solar diffuser view data. The VIIRS Data Interface Control Document *[Y2470]* describes these data.

3.3 THEORETICAL DESCRIPTION

The MODIS Level 1B ATBD *[ref. Barnes, Pagano, and Salomonson (1998), Guenther et al (1998), and MCST (1997)]* contains many details about transferring MODIS pre-launch calibration to MODIS on-orbit data. These details include corrections to raw instrument counts to account for non-linearities in analog to digital conversion, detector specific response characteristics, focal plane temperature, and scan angle effects. It can be anticipated the type of corrections that are applied to MODIS will also have to be used during VIIRS radiometric calibration. At the time of this writing the VIIRS has not undergone any of the pre-launch calibration tests that are necessary to define these corrections. Therefore this version of the VIIRS Radiometric Calibration ATBD presents a basic mathematical description of radiometric calibration and recognizes the need to accommodate corrections and adjustments as a practical consideration for the design of the VIIRS radiometric calibration software.

Terminator orbits present a special challenge for the radiometric calibration of VIIRS reflective bands. When in a terminator orbit (i.e. the 17:30 local equator crossing time orbit) the VIIRS solar diffuser will not be illuminated by the Sun. A procedure for calibration transfer from non-terminator orbits to terminator orbits is presented in Terminator Orbit Calibration *[Y6875]*. This procedure uses coincident nadir Earth scenes from the 13:30 orbit (which will have nearly identical solar zenith angles) to adjust the calibration of the 17:30 orbit.

Separate algorithms are presented in the following subsections for the VIIRS reflective bands and for the VIIRS emissive bands. Due to its unique design and performance requirements the VIIRS Day/Night Band (DNB) radiometric calibration is treated separately in Section .3.3.3.

3.3.1 Reflective Bands

Reflective VIIRS bands include moderate resolution bands M1 through M11, imagery resolution bands I1, I2, and I3, and the DNB (which is discussed in Section 3.3.3). The two types of moderate resolution reflective VIIRS bands (i.e. single gain and dual gain) are processed somewhat differently. All imagery resolution bands are single gain. TOA reflectances and TOA radiances are computed and stored in the SDR files for each reflective band pixel. In addition TOA brightness temperatures are also computed for three reflective bands that are expected to be emissive for fires; i.e. M7, M8, and M10.

3.3.1.1 Single Gain Reflective Bands

The single gain reflective bands are the I1, I2, and I3 imagery resolution bands and the M6, M8, M9, M10, and M11 moderate resolution bands.

Predetermined correction and conversion factors that are adjusted for variations in incoming solar irradiance and to account for instrument degradation are applied to the VIIRS DN resulting in calibrated TOA reflectances and TOA radiances. For those reflective bands that are expected to be emissive for fires, the TOA radiances are converted to TOA brightness temperatures. The steps in this process are as follows:

1) Correct raw DN for analog to digital conversion (ADC) non-linearity by adding a pre-determined ADC correction factor that is read from a LUT. The correction is specific for each band and is also a function of which electronic system (i.e. primary or redundant) is in use and the digital number itself.

2) Remove detector response when no signal is present by subtracting the zero offset. Zero offset is determined on a scan-by-scan basis for each detector using space view data. DNs from the central part of the space view segment are averaged to determine zero offset. In the event that the Moon corrupts the central part of the segment, other minimum signal samples from the space view segment are used.

3) Additional corrections are applied to account for instrument and focal plane array (FPA) temperature effects and response versus scan (RVS) effects. The temperature correction factors are specific for each band-detector-half angle mirror (HAM) side combination. The RVS correction is band-detector-HAM side as well as scan angle dependent.

$$DN_{corrected} = DN_{adjusted} * (1 + k_{inst} * [T_{inst} - T_{reference})] / RVS \qquad (1)$$

where $DN_{adjusted}$ is the DN after correction for A-D non-linearity and subtraction of zero offset, k_{inst} is an instrument temperature correction factor read from the reflective calibration LUT, T_{inst} is the instrument temperature, $T_{reference}$ is a reference instrument temperature read from the reflective calibration LUT, and RVS is the response versus scan angle correction.

4) After these corrections to DN are complete a conversion to TOA reflectance is made using detector-HAM side dependent calibration coefficients

$$\rho_{TOA} = m_0 + m_1 * (DN_{corrected} + 0.5) * d^2 / \cos(\theta) \qquad (2)$$

where m_0 and m_1 are the constant and linear DN to reflectance calibration coefficients as read from the reflective LUT, d is the Earth-Sun distance, and $\cos(\theta)$ is the cosine of the solar zenith angle measured from the normal to the Earth.

5) Corrected DN are then converted to TOA radiance in W/m^2-sr-µm using a pre-determined band-detector-HAM side dependent radiance gain factor

$$L_{TOA} = DN_{corrected} * G \qquad (3)$$

where G is the radiance gain factor as read from the reflective LUT.

6) If processing either the M7, M8, or M10 band then TOA radiance is then converted to TOA brightness temperature using the following equation

$$T_b = c_2\, \nu / \ln(1 + c_1\, \nu^3 / R) \qquad (4)$$

where c_1 and c_2 are two blackbody constants equal to 0.01191071 and 1.438838 respectively using cgs units, ν is the wavenumber (cm^{-1}), and T is temperature in Kelvins

The monochromatic radiance (R) is

$$R = L_{TOA}/(bandwidth) \qquad (5)$$

where L_{TOA} is the top of the atmosphere radiance given by the calibration algorithm and the bandwidth equals the difference between the upper and lower wavelengths of the band in nm (i.e., full width at half maximum).

The correction and conversion factors used in this process are initially determined during pre-launch testing then updated based on analysis of solar diffuser and solar diffuser stability monitor data. They are stored as LUTs in a reflective band processing input parameter file (see VIIRS Radiometric Calibration Unit Level Detailed Design *[Y2490]*). A separate reflective LUT file is used for each VIIRS sensor. Details concerning the generation of the pre-launch correction factors and conversion coefficients can be found in the VIIRS Characterization and Calibration Plan *[TP 154640-118]*. During the operational phase of each sensor adjustments may be made to these LUTs from time to time based on offline analysis of sensor performance. In general these factors are given for each band-detector-HAM side combination and include corrections for RVS.

The LUTs for the reflective bands are summarized in Table 3. The VIIRS Radiometric Calibration Unit Level Detailed Design *[Y2490]* describes these LUTs in detail.

Table 3. Reflective Band LUTs

LUT	Dimensions
Radiance Gain Factor	(band, detector, HAM side, gain state)
Reflectance Calibration Factors (‘m_0’ constant term and ‘m_1’ linear term)	(band, detector, HAM side, gain state)
Instrument and FPA Temperature Correction Factors	(band, detector, HAM side, gain state)
Instrument Temperature Reference	constant
FPA Temperature Reference	(FPA)
RVS Correction Factor	(band, detector, sample, HAM side)
ADC Correction Factors	(electronics system, band, DN value)
Minimum and Maximum Radiance	(band)
Bandcenter	(band, detector)
Bandwidth	(band, detector)

3.3.1.2 Dual Gain Reflective Bands

The dual gain reflective bands are M1, M2, M3, M4, M5, and M7. The radiometric calibration of these dual gain reflective bands is similar to the radiometric calibration of the single gain reflective bands except for the determination of zero offsets, the size and selection of the LUTs, and the packaging of the calibrated products.

In the case of the dual gain bands the current plan is to view calibrator sources using a single gain range on one scan then using the other gain range on the subsequent scan. Therefore a complete set of HAM side dependent zero offsets will be acquired every four scans. The radiometric calibration algorithm selects the appropriate zero offset to use when processing a scan by selecting from the most recent value computed from space view data that was taken with the same gain range and HAM side as that of the Earth view scene being processed.

Gain specific correction and conversion factors are stored as LUTs for use with the dual gain reflective bands. This adds a dimension to each factor and introduces the requirement on the processing software to identify and select the correct values to use for each sample.

Following radiometric calibration of each dual gain DN an along-track aggregation is performed as part of the process of building the output SDR products to exactly match the aggregation that is performed on-board for the single gain bands. TOA reflectances and TOA radiances for the unaggregated sub-pixel samples that would otherwise be discarded are saved in the Calibrated Dual Gain IP file for analysis or production of special interest products that may be desired from time to time. The Calibrated Dual Gain IP file is described in detail in the VIIRS Radiometric Calibration Unit Level Detailed Design *[Y2490]*.

3.3.2 Emissive Bands

Emissive VIIRS bands include moderate resolution bands M12 through M16 and imagery resolution bands I4 and I5. There are three types of moderate resolution emissive VIIRS bands (single gain, dual gain, and dual output). All imagery resolution bands are single gain. TOA radiances and TOA brightness temperatures are computed and stored in the SDR files for each emissive band pixel.

3.3.2.1 Single Gain Emissive Bands

The single gain emissive bands are the I4 and I5 imagery resolution bands and the M12, M14, M15, and M16 moderate resolution bands. The dual output M16 band is discussed separately in Section 3.3.2.3. Calibrated TOA radiances are derived by multiplying each input Earth view DN (after removal of zero signal background and adjustment for analog-to-digital non-linearity) by the appropriate temperature dependent calibration gain, and then adding the appropriate calibration offset. The background signal (i.e. zero offset) is computed on a scan-by-scan basis from space view data and the gain factor used for conversion of DN to radiance is adjusted for each scan using observed blackbody radiance. TOA brightness temperatures are then computed from the TOA radiances and both products are stored in the output SDR files.

The steps in the radiometric calibration of the single gain emissive bands are as follows:

1) Correct raw DN for analog to digital conversion non-linearities by applying pre-determined ADC correction factors. The correction is specific for each band and is also a function of which electronic system (i.e. primary or redundant) is in use and the digital number itself.

2) Remove detector response during the space view when no detectable signal is present (i.e. the zero offset). Zero offset is determined on a scan-by-scan basis for each detector using space view data. DNs from the central part of the space view segment are averaged after analog-to-digital correction to determine zero offset. In the event that the Moon corrupts the central part of the segment then other minimum signal samples from the space view segment are used.

3) After these changes to DN are complete a conversion to TOA radiance in W/m^2-sr-µm is made using detector-HAM side specific calibration coefficients that are functions of instrument temperature and are referenced to observed blackbody radiance

$$R_{TOA} = a_0{*}T_{inst} + b1{*}DN_{adjusted} + a_2{*}T_{inst}\,{*}DN_{adjusted}^{\;2} \tag{6}$$

where a_0 and a_2 are calibration coefficients read from emissive calibration LUT, T_{inst} is the instrument temperature, $DN_{adjusted}$ is the DN after correction for A-D non-linearity and subtraction of zero offset, and b_1 is computed for a scan as follows:

$$b_1=(\varepsilon_{BB}*L_{BB}+[RVS_{SV}-1]*L_{HAM}+[1-\varepsilon_{BB}]*\varepsilon_{cav}*L_{cav}-a_0*T_{inst}-a_2*T_{inst}*DN_{BB}^{2})/DN_{BB} \quad (7)$$

where ε_{BB} is the emissivity of the blackbody read from the emissive calibration LUT, L_{HAM} is blackbody radiance, RVS_{SV} is response versus scan for the space view as read from emissive calibration LUT, L_{HAM} is RVS corrected HAM radiance, ε_{cav} is the emissivity of the instrument cavity read from the emissive calibration LUT, L_{cav} is instrument cavity radiance, a_0 and a_2 are calibration coefficients read from emissive calibration LUT, T_{inst} is the instrument temperature, and DN_{BB} is the average blackbody DN after correction for zero offset.

4) Resultant TOA radiance is then corrected for RVS using RVS coefficients that are detector-HAM side specific and have been adjusted for temperature

$$L_{TOA} = (R_{TOA} - L_{HAM}) / RVS \quad (8)$$

where L_{HAM} is RVS corrected HAM radiance. and RVS is response versus scan read from emissive calibration LUT

5) Corrected TOA radiance is then converted to TOA brightness temperature using the following equation

$$T_b = c_2\, \nu / ln(1 + c_1\, \nu^3 / R) \quad (9)$$

where c_1 and c_2 are two blackbody constants equal to 0.01191071 and 1.438838 respectively using cgs units, ν is the wavenumber (cm^{-1}), and T is temperature in Kelvins

The monochromatic radiance (R) is

$$R = L_{TOA}/(bandwidth) \quad (10)$$

where L_{TOA} is the top of the atmosphere radiance given by the calibration algorithm and the bandwidth equals the difference between the upper and lower wavelengths of the band (i.e., full width at half maximum).

The correction and conversion factors used in this process are initially determined during pre-launch testing then updated based on analysis of blackbody data. They are stored as LUTs in an emissive band processing input parameter file (see VIIRS Radiometric Calibration Unit Level Detailed Design *[Y2490]*). A separate emissive LUT file is used for each VIIRS sensor. Details concerning the generation of the pre-launch correction factors and conversion coefficients can be found in the VIIRS Characterization and Calibration Plan *[TP 154640-118]*. During the operational phase of each sensor adjustments may be made to these LUTs from time to time based on offline analysis of sensor performance. In general these factors are given for each detector-HAM side combination and include corrections for RVS.

The LUTs for the emissive bands are summarized in Table 4. The VIIRS Radiometric Calibration Unit Level Detailed Design *[Y2490]* describes these LUTs in detail.

Table 4. Emissive Band LUTs

LUT	Dimensions
Blackbody and Scan Cavity Emissivities	(band, detector)
BB Temperature Correction Terms β and δ $\Delta T_{BB} = \beta(T_{CAV} - T_{BB}) + \delta$	(band, detector)
RVS Correction Factor	(band, detector, sample, HAM side)
Polynomial Coefficients for $a_0(T)$ and $a_2(T)$ $a_0 = A_0[0] + A_0[1]*T + A_0[2]*T^2$ (constant term for L vs. DN) $a_2 = A_2[0] + A_2[1]*T + A_2[2]*T^2$ (quadratic term for L vs. DN)	(coefficient, band, detector, HAM side, gain state)
Relative Spectral Response	(band, detector, points)
Relative Spectral Response Wavelengths	(band, detector, points)
Number of Relative Spectral Response Points	(band, detector)
ADC Correction Factors	(electronics system, band, DN value)
Minimum and Maximum Radiance	(band)
Bandcenter	(band, detector)
Bandwidth	(band, detector)

3.3.2.2 M13 Dual Gain Emissive Band

The M13 band is the sole dual gain emissive band. The radiometric calibration of this dual gain emissive band is similar to the radiometric calibration of the single gain emissive band except for the determination of zero offsets, the size and selection of the LUTs, and the packaging of the calibrated products.

In the case of the dual gain M13 band the current plan is to view calibrator sources using a single gain range on one scan then using the other gain range on the subsequent scan. Therefore a complete set of HAM side dependent zero offsets will be acquired every four scans. The radiometric calibration algorithm selects the appropriate zero offset to use when processing a scan by selecting from the most recent set that contains space view data taken with the same gain range and HAM side as that of the Earth view scene being processed.

Gain specific correction and conversion factors are stored as LUTs for use with the dual gain M13 emissive band. This adds a dimension to each factor and introduces the requirement on the processing software to identify and select the correct values to use for each scene.

Following radiometric calibration of the M13 DNs an along-track aggregation is performed as part of the process of building the output SDR products to exactly match the aggregation that is performed on-board for the single gain bands. The unaggregated scenes that would otherwise be discarded are saved in the Calibrated Dual Gain IP file for analysis or production of special interest products that may be desired from time to time.

3.3.2.3 M16 Dual Output Emissive Band

The M16 band is unique to VIIRS as it is the only dual output band. The two along track lines of M16 detectors are combined on-board to create one set of transmitted DNs for each sample. Prior to this on-board combination DNs from the second line are adjusted to match the gain and offset of the first line. The ground processing radiometric calibration of the M16 dual output band proceeds exactly like the single gain emissive bands (see Section 3.3.2.3) treating the combined DN as if it came from one single gain emissive band.

3.3.3 Day/Night Band

The radiometric calibration algorithm for the DNB is similar to the dual gain moderate resolution reflective band calibration except that coefficients are carried for each of the 32 along-scan aggregation zones and gain state dependent parameters require three vs. two values to cover each of the DNB gain states. Temperature control of the DNB ensures that it meets its performance specifications without applying a temperature correction during radiometric calibration.

As computed the DNB calibrated TOA radiances will be spectral radiance in W/m^2-sr-μm (as will be the case with other bands). However users of this product prefer integrated radiance in W/cm^2-sr. Therefore a conversion to W/cm^2-sr will be performed prior to storing in the DNB SDR files. The correction factor is determined from each sensor's DNB spectral response function and is stored in the DNB LUT.

3.4 PRACTICAL CONSIDERATIONS

3.4.1 Numerical Computation Considerations

Paragraph SRDV3.2.1.5.4-1 of the VIIRS SRD states the following:

> "*The scientific SDR and EDR algorithms delivered by the VIIRS contractor shall be convertible into operational code that is compatible with a 20 minute maximum processing time at either the DoD Centrals or DoD field terminals for the conversion of all pertinent RDRs into all required EDRs for the site or terminal, including those based wholly or in part on data from other sensor suites*."

This essentially means that any and all EDRs must be completely processed from VIIRS raw data, including calibration and georeferencing within 20 minutes from the time the raw data are available. This requirement is a strong reminder that VIIRS is an operational instrument.

The calculations used for VIIRS radiometric calibration are very similar to those perform as part of routine MODIS processing and are therefore expected to perform within a reasonable allocation of the operational timeline. Furthermore the calculations to convert calibrated TOA reflectances to calibrated TOA radiances and from calibrated TOA radiances to calibrated TOA brightness temperatures are straightforward and leave minimal additional impact on VIIRS processing resources.

3.4.2 Programming and Procedural Considerations

It is expected that some adjustments will have to be made to the calibration coefficients and/or radiance/reflectance values to account for on-orbit changes in instrument characterization and to account for small differences in individual detector throughput and the optical characteristics of the two sides of the VIIRS HAM. The nature of these adjustments may not be known before the VIIRS Radiometric Calibration software is complete. Therefore, through the use of external band-detector-HAM side LUTs, the VIIRS software architecture has been designed to be flexible enough to accommodate adjustments if and when needed.

Details of the software for radiometric calibration are presented in the VIIRS Context Software Architecture *[Y2469]*, the VIIRS Build SDR Module Level Software Architecture *[Y2479]*, and the VIIRS Radiometric Calibration Unit Level Detailed Design *[Y2490]*. The efficient storage of the SDR products is detailed in *[Y2490]*.

3.4.2.1 Quality Control

The VIIRS radiometric calibration algorithm includes many checks on the reasonableness of input data and output product. The quality bit assigned to each pixel's TOA radiance, TOA reflectance, and TOA brightness temperature is set should some problem be detected during radiometric calibration. This quality bit serves as a flag to the subsequent EDR generation algorithms to avoid using such a pixel.

3.4.2.2 Exception Handling

Warning and error messages that may be issued during radiometric calibration are stored in a log file and appropriate return codes are set to control program action and to communicate status to system process control software. Details of exception handling are in the VIIRS Radiometric Calibration Unit Level Detailed Design *[Y2490]*.

3.4.3 Initialization

Initialization is accomplished by populating the reflective, emissive, and DNB LUTs. Prior to launch of each sensor these LUTs are constructed using the best available analysis results from pre-launch sensor testing.

4.0 ASSUMPTIONS AND LIMITATIONS

4.1 ON-BOARD PROCESSING

It is assumed that onboard processing will aggregate the imagery resolution and single gain moderate resolution band DNs as is described in Section 2.2. Furthermore it is assumed that the DNB will be operated and the on-board data processing will be performed according to the DNB CCA Product Specification for VIIRS *[PS154640-380]*, the DNB Module Performance Specification NPOESS *[PS154640-124]*, and the Digital Preprocessor Product Specification for VIIRS *[PS154640-360]*..

4.2 INPUT DATA

It is assumed that the reflective band, emissive band, and DNB LUTs will be populated with complete and correct calibration parameters. It is assumed that the RDR input is as described in the VIIRS Build RDR Module Level Detailed Design *[Y2487]* and that geolocation data will be available as described in the VIIRS Geolocation Unit Level Detailed Design *[Y3245]*.

4.3 PRE-LAUNCH CALIBRATION

It is assumed that pre-launch calibration for each sensor will be adequate to characterize the sensor and provide the data needed for the reflective, emissive, and DNB radiometric calibration LUTs.

5.0 REFERENCES

5.1 VIIRS DOCUMENTS

The following VIIRS documents are referenced in this ATBD using their Raytheon SBRS document number in italicized brackets, e.g., *[Y12345]*:

[PS154640-102]	Performance Specification Algorithm Specification for the VIIRS
[PS154640-124]	DNB Module Performance Specification NPOESS
[PS154640-360]	Digital Preprocessor Product Specification for VIIRS
[PS154640-380]	DNB CCA Product Specification for VIIRS
[TP154640-001]	VIIRS System Verification and Validation Plan
[TP154640-118]	VIIRS Characterization and Calibration Plan
[Y2388]	VIIRS Software Development Plan
[Y2469]	VIIRS Context Software Architecture
[Y2470]	VIIRS Data Interface Control Document
[Y2479]	VIIRS Build SDR Module Level Software Architecture
[Y2487]	VIIRS Build RDR Module Level Detailed Design
[Y2490]	VIIRS Radiometric Calibration Unit Level Detailed Design
[Y3245]	VIIRS Geolocation Unit Level Detailed Design
[Y3258]	VIIRS Geoocation ATBD
[Y5563]	Closure Memo for VIIRS PDR Action Items 29, 43, 47, and 78
[Y6875]	Terminator Orbit Calibration

5.2 NON-VIIRS DOCUMENTS

The following non-VIIRS documents are references for this ATBD:

Barnes, W.L., Thomas S. Pagano, and Vincent V. Salomonson, (July 1998), Prelaunch Characteristics of the Moderate Resolution Imaging Spectroradiometer (MODIS) on EOS-AM1, IEEE Transactions on Geoscience and Remote Sensing, Vol. 36, No. 4, July 1998. 13 pp.

Guenther, B. et al, (July 1998), Prelaunch Algorithm and Data Format for the Level 1 Calibration Products for the EOS-AM1 Moderate Resolution Imaging Spectroradiometer (MODIS), IEEE Transactions on Geoscience and Remote Sensing, Vol. 36, No. 4, July 1998. 10 pp.

IPO (2000). Visible/Infrared Imager/Radiometer Suite (VIIRS) Sensor Requirements Document (SRD) for National Polar-Orbiting Operational Environmental Satellite System (NPOESS) spacecraft and sensors, Rev. 2b/c. Prepared by Assoc. Directorate for Acquisition, NPOESS Integrated Program Office, Silver Spring, MD.

MODIS Characterization Support Team (May 1997). MODIS Level 1B Algorithm Theoretical Basis Document Version 2.0, MCST Document #MCM-ATBD-01-U-DNCN, NASA/GSFC, Greenbelt, MD.

MODIS Characterization Support Team (2000). MODIS Level 1B Product User's Guide, For Level 1B Version 2.3.x, Release 2, MCST Document #MCM-PUG-01-U-DNCN, NASA/GSFC, Greenbelt, MD.

Planet, W.G. (ed.), (1988). Data extraction and calibration of TIROS-N/NOAA radiometers. NOAA Technical Memorandum NESS 107 – Rev. 1, Oct. 1988. 130 pp.